Relic Supernova Neutrinos:

How to See Some More Supernova Neutrinos – In the Next Few Years

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A long time ago, in a (neighbor) galaxy far, far away…

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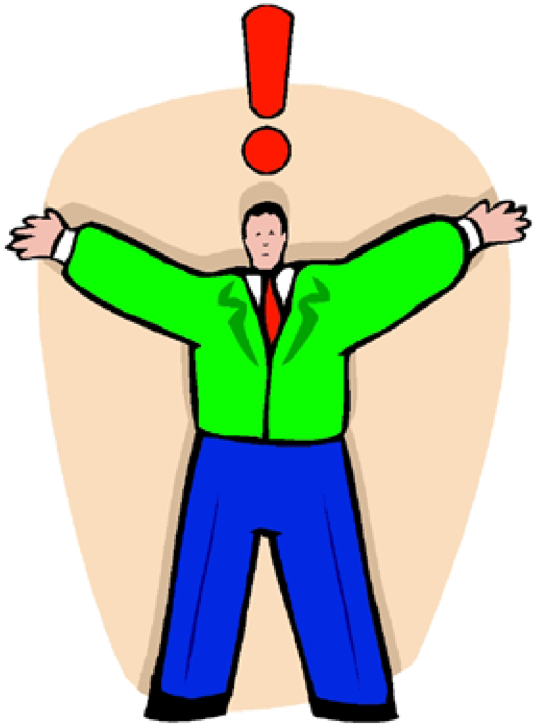
On February 23^{rd} we celebrated a big anniversary…

Twenty years since SN1987A!

Based on the handful of supernova neutrinos which were detected that day, approximately <u>one theory paper has been published every ten days</u>…

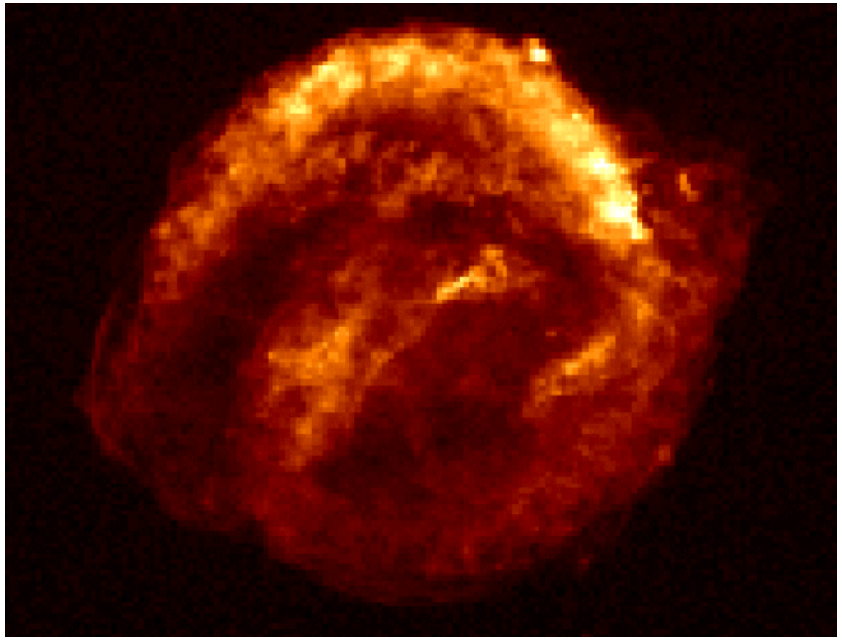
…for the last twenty years!

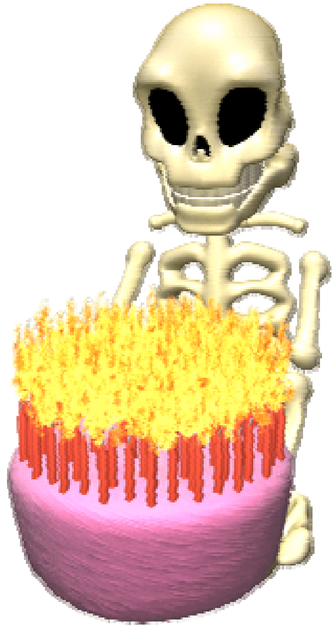
But on the other hand…



It's been *twenty years* since SN1987A!

We've had essentially continuous ν coverage of the whole galaxy for over 25 years, but no other SN ν's have been seen.





Even worst, it has been 402 years and 156 days since a supernova was last definitely observed within our own galaxy!

Of course, no neutrinos were recorded that mid-October day in 1604…
but it was probably a type Ia, anyway.

So, how can we see some more supernova neutrinos without having to wait too long?

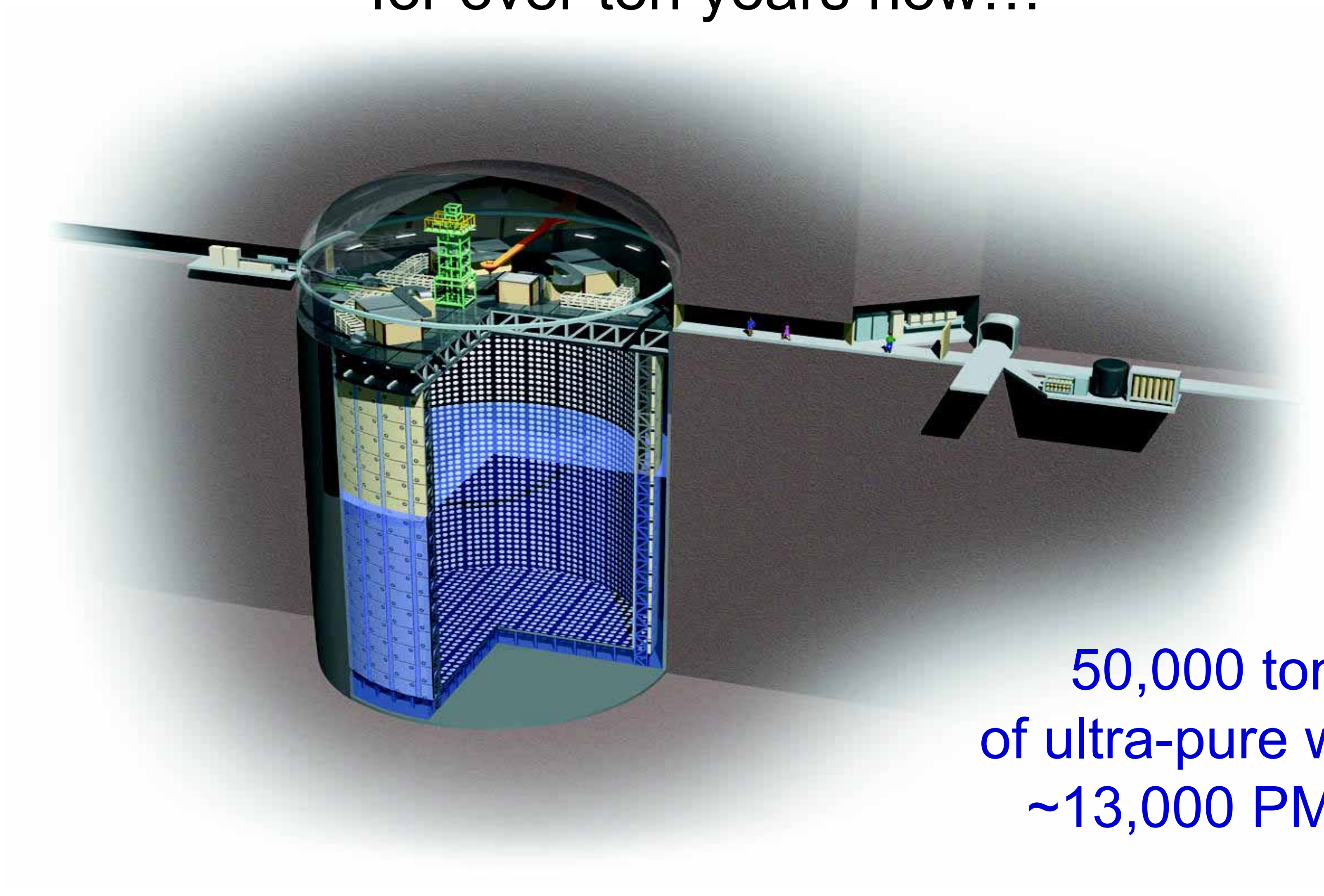
Well, *galactic* supernovas may be somewhat rare on a human timescale, but supernovas are not.

On average, there is one supernova explosion somewhere in our universe every second.

These make up the diffuse supernova neutrino background [DSNB], also known as the “relic” supernova neutrinos.

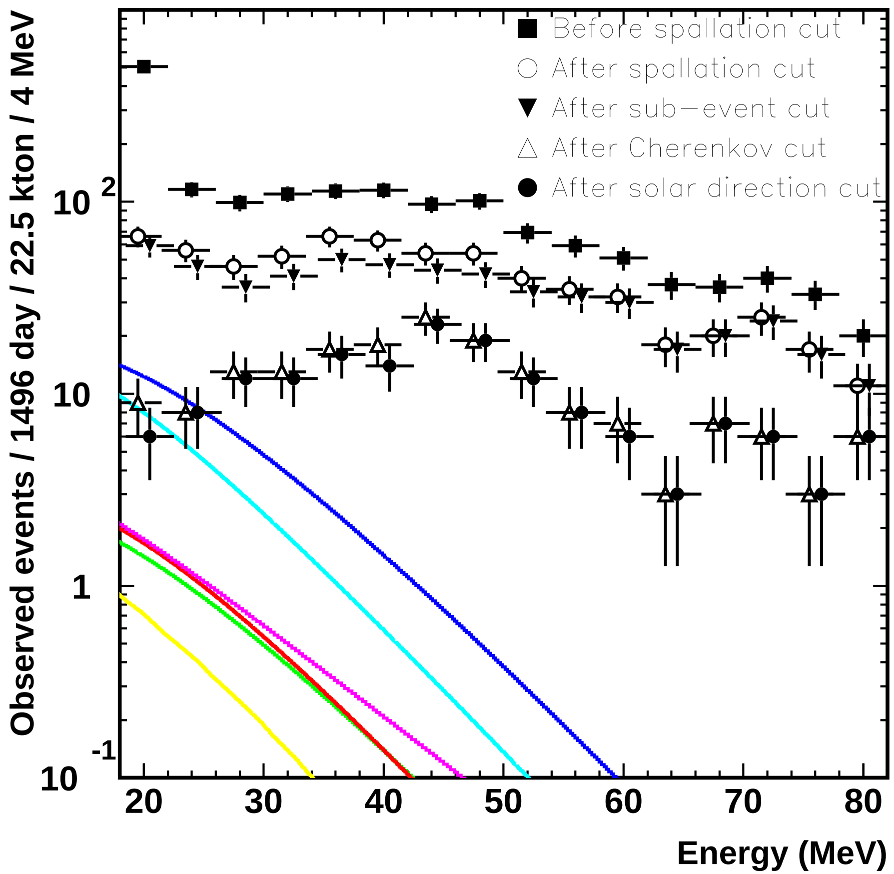
After traveling an average distance of *six billion light years,* about 100,000 of these genuine supernova neutrinos pass through our bodies every second.

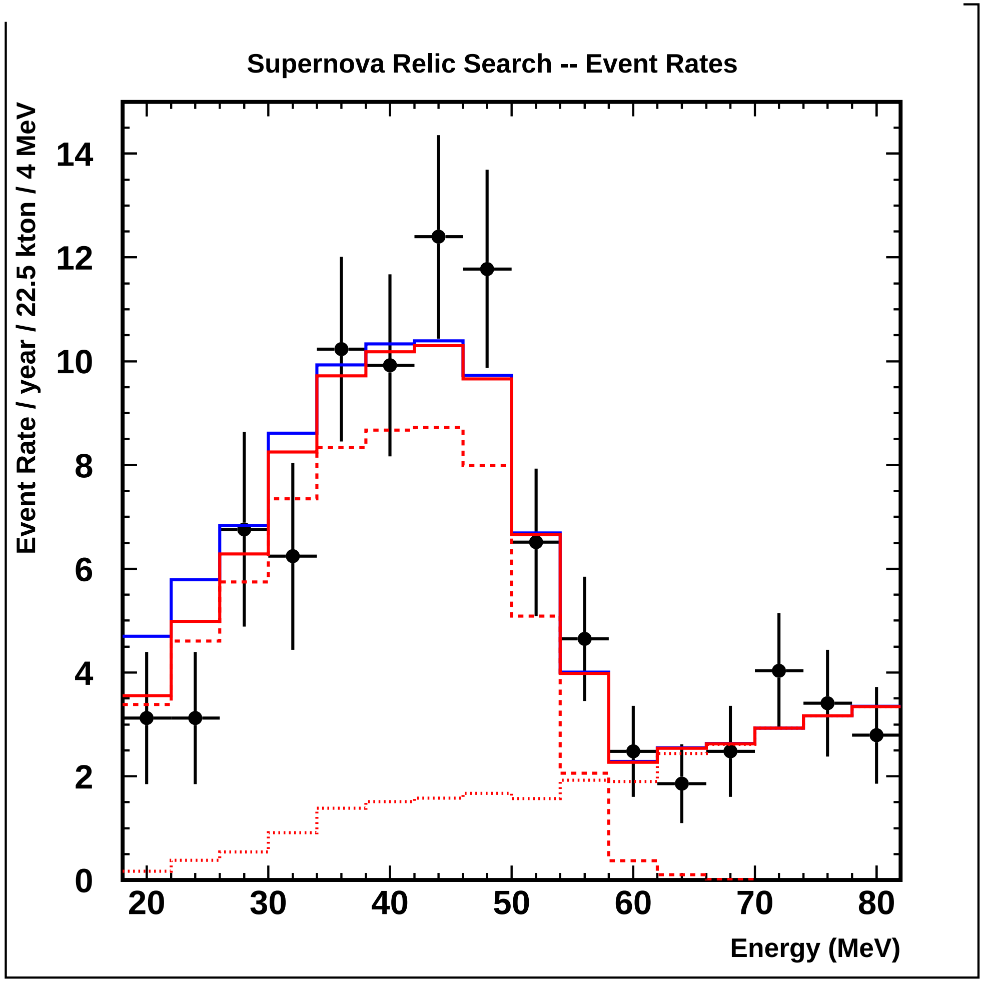
My beloved Super-Kamiokande
– already the best DSNB detector in the world –
has been taking data, with an occasional interruption,
for over ten years now…



50,000 tons
of ultra-pure water,
~13,000 PMT’s

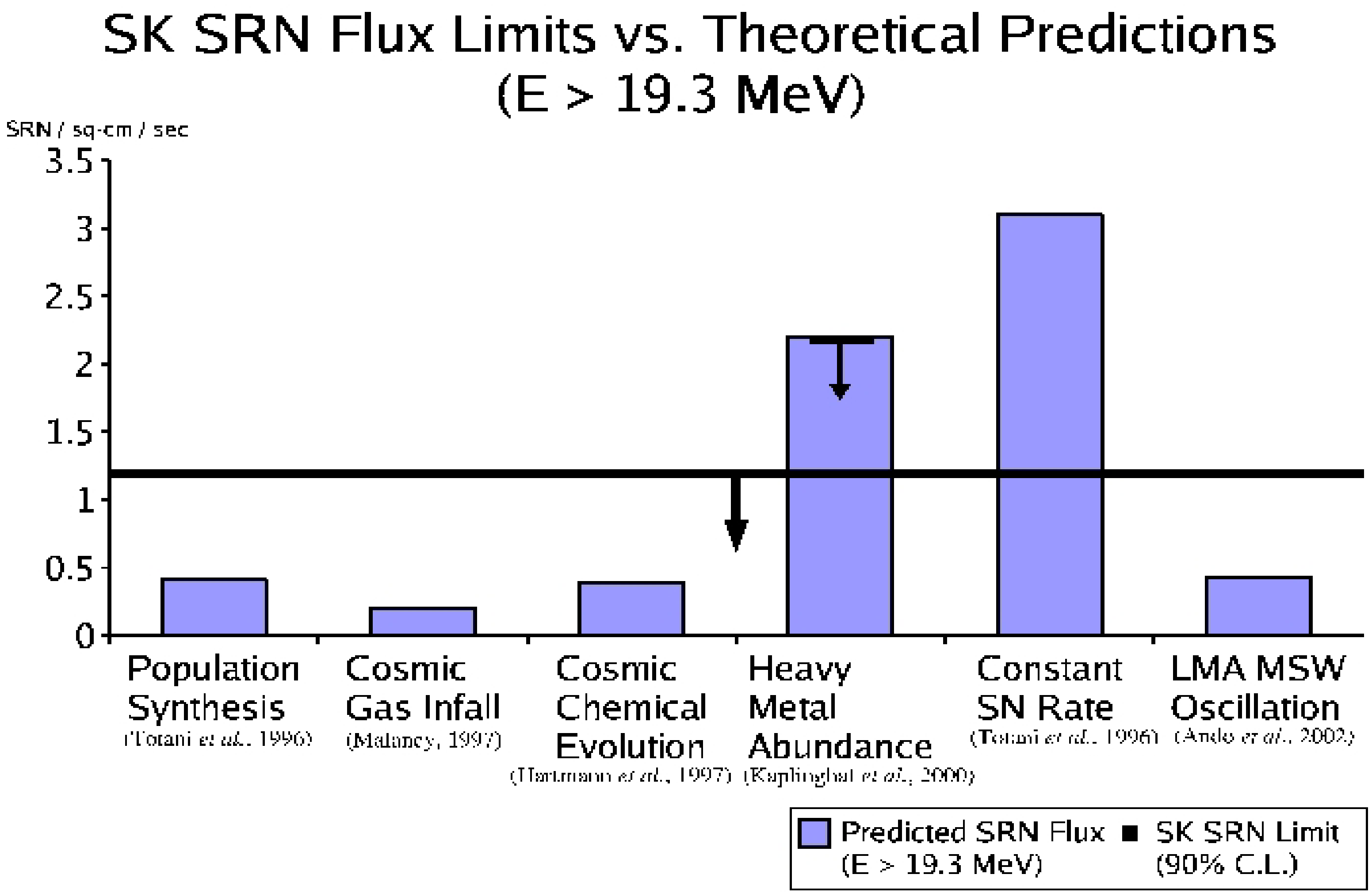
In 2003, Super-Kamiokande published the world's best limits on this so-far unseen $\overline{\nu}_e$ flux [M.Malek *et al., Phys. Rev. Lett.* **90** 061101 (2003)].





Unfortunately, this search was strongly limited by backgrounds, and no event excess was seen.

Here's how the SK result constrained the existing models:



Experimental DSNB limits are approaching theoretical predictions. Clearly, reducing the remaining backgrounds and going lower in energy would be extremely valuable. But how?

Well, all of the events in the present SK analysis are <u>singles</u> in time and space.

And this rate is actually very low… just <u>three events per cubic meter per *year.*</u>

So, in 2002, John Beacom and I started working on a method to improve the SK detector in order to actually observe the DSNB signal for the first time.

[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

“Wouldn’t it be great,” we thought, “if there was a way to tag every DSNB event in Super-K?”

Since the reaction we are looking for is

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

what if we could reliably identify the neutron (currently invisible in Super-K) and look for coincident signals?

But we're going to have to compete with hydrogen

$(p + n \rightarrow d + 2.2\ \mathrm{MeV}\ \gamma)$

in capturing the neutrons!

Plus, plain old NaCl isn't going to work…

We'd need to add 3 kilotons of salt to SK just to get 50% of the neutrons to capture on the chlorine!

So, we eventually turned to the best neutron capture nucleus known – gadolinium.

- $GdCl_3$, unlike metallic Gd, is highly water soluble
- Neutron capture on Gd emits a 8.0 MeV γ cascade
- 100 tons of $GdCl_3$ in SK (0.2% by mass) would yield >90% neutron captures on Gd
- Plus, it's not even particularly toxic!

But, um, didn't you just say 100 *tons?*
What's that going to cost?

In 1984: $4000/kg –> $400,000,000

In 1993: $485/kg –> $48,500,000

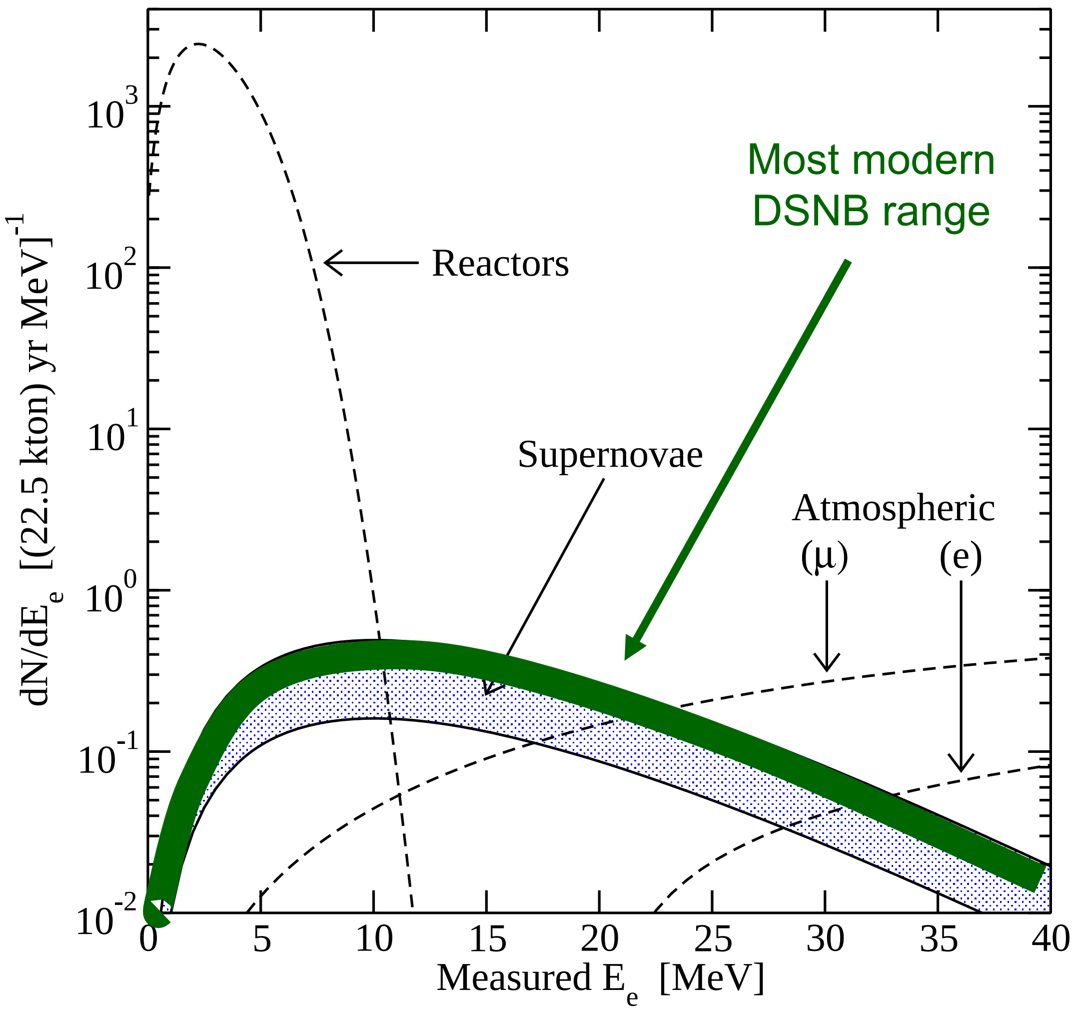
In 1999: $115/kg –> $11,500,000

In 2007: $5/kg –> $500,000

Our proposed name for this water Cherenkov upgrade:

Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super**!**

Here's what the coincident signals in Super-K-III with $GdCl_3$ will look like (energy resolution is applied):



Adding 100 tons of $GdCl_3$ to Super-K would provide us with at least two brand-new, guaranteed signals:

1)Precision measurements of the neutrinos from all of Japan's power reactors
(~5,000 events per year)
Will improve world average precision of Δm^2_{12} by 10X

2) Discovery of the diffuse supernova neutrino background [DSNB], also known as the "relic" supernova neutrinos
(~5 events per year)

In addition to our two guaranteed new signals, it is likely that adding $GdCl_3$ to SK-III will provide a variety of other interesting (and not yet fully explored) possibilities:

- Sensitivity to very late-time black hole formation
- Full de-convolution of a galactic supernova's ν signals
- Early warning of an approaching SN ν burst
- (Free) proton decay background reduction
- New long-baseline flux normalization for T2K
- Matter- vs. antimatter-enhanced atmospheric ν samples(?)

Indeed, the physics case for GADZOOKS! seems very strong. But can we make it work in the real world?

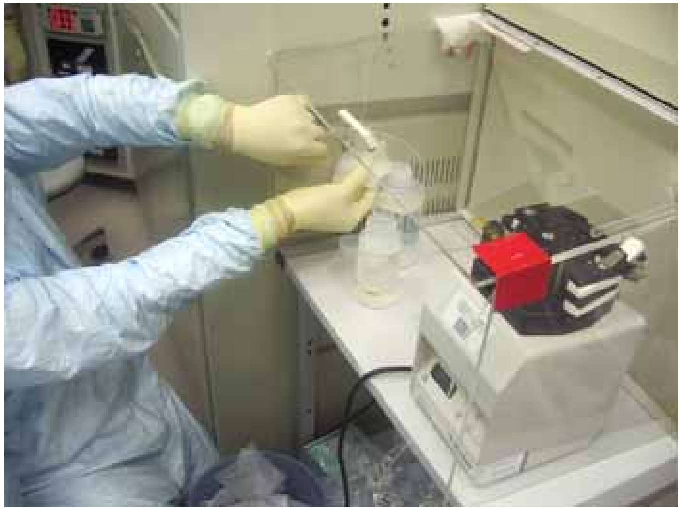
You see, Beacom and I never wanted to merely propose a new technique – we wanted to make it work!

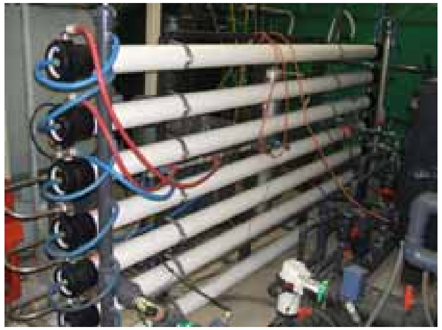
Now, suggesting a major modification of one of the world's leading neutrino detectors may not be the easiest route…

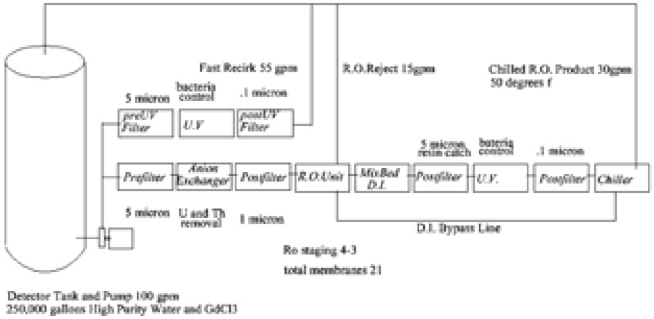
…and so to avoid wiping out, some careful hardware studies would be needed.

- What does $GdCl_3$ do the Super-K tank materials?
- Will the resulting water transparency be acceptable?
- Any strange Gd chemistry we need to know about?
- How will we filter the SK water but retain $GdCl_3$?

So, over the last four years there have been a large number of $GdCl_3$-related R&D studies carried out in the US and Japan:







At Super-K, a new calibration source using $GdCl_3$ has been developed and deployed inside the detector:

Am/Be source

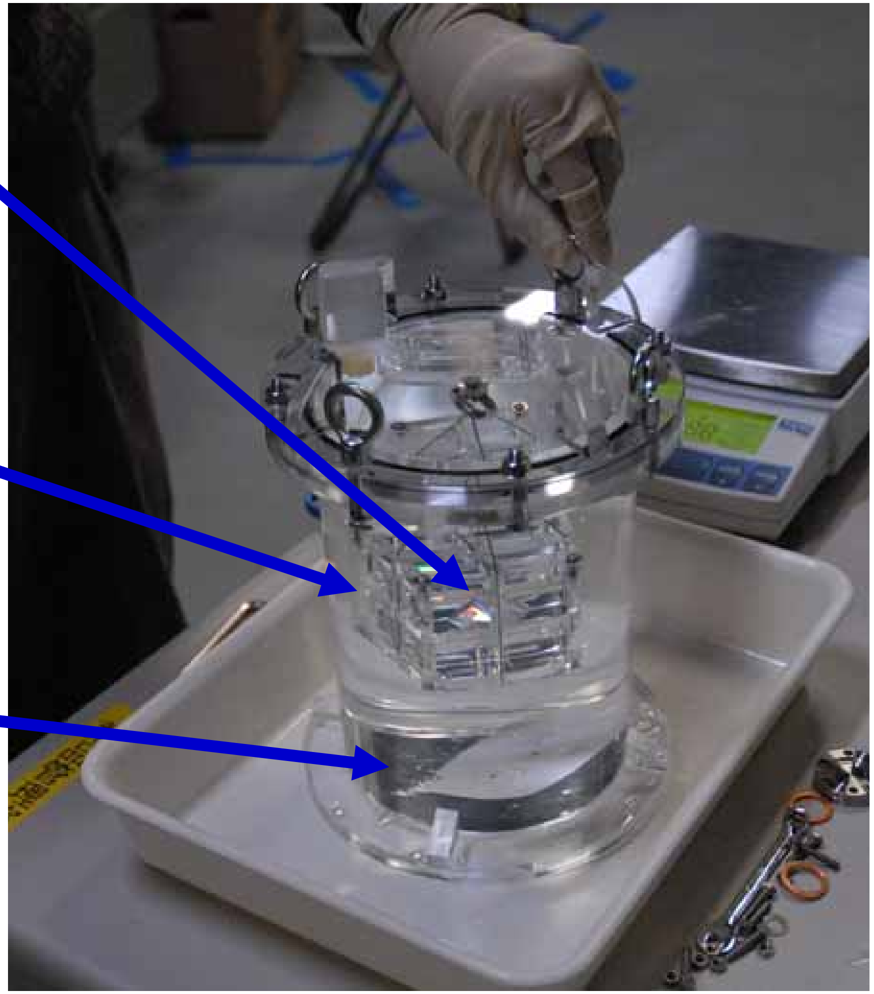
$\alpha + {}^{9}Be \rightarrow {}^{12}C^* + n$

${}^{12}C^* \rightarrow {}^{12}C + \gamma(4.4\ \text{MeV})$

Inside a BGO crystal array

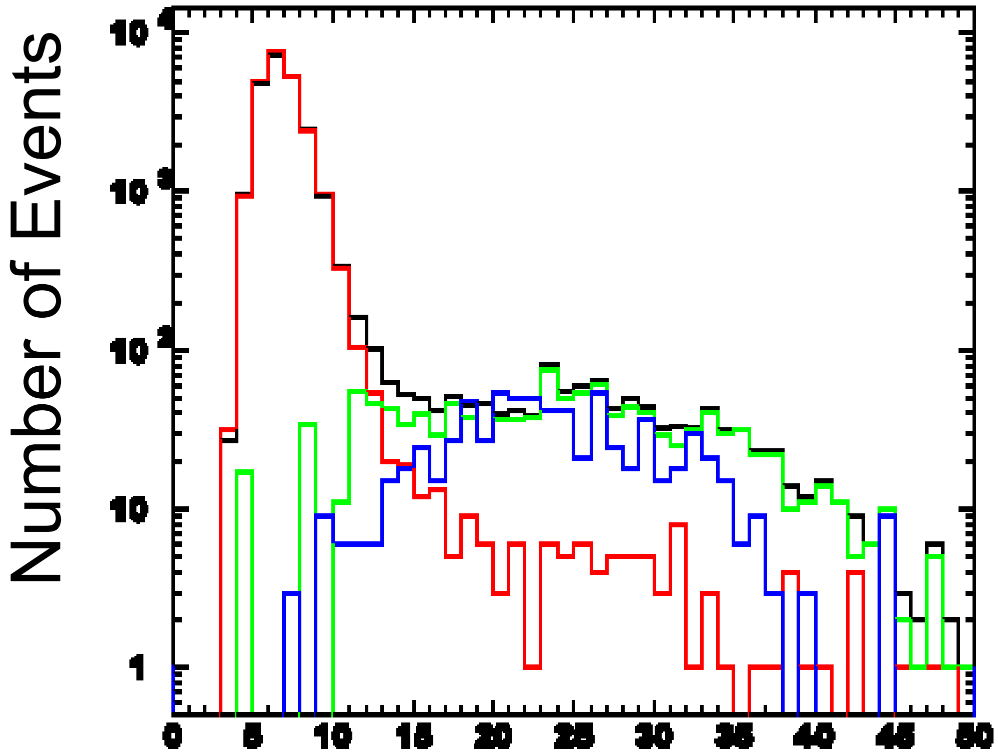
(BGO = $Bi_4Ge_3O_{12}$)

Suspended in 2 liters of 0.2% $GdCl_3$ solution



Data was taken for the first time four weeks ago.

We've made the world's first "spectrum" of $GdCl_3$'s neutron capture gammas producing Cherenkov light!



Black: On-time events
Red: Off-time events
Green: Black-Red
Blue: MC Prediction

More study (and data) needed, but a really promising early result!

Also, first $GdCl_3$ "in" SK!

N_{50} = max PMT hits within 50 ns sliding window

To conclude:

1) The physics case for GADZOOKS! is very strong.

2) R&D is active and ongoing in US and Japan; total investigative funding has exceeded $300,000 so far.

3) Some challenges remain (technical, environmental), but we on Super-K share the community's powerful desire for new supernova events and new physics.

4) Therefore, I boldly predict that by the 25th anniversary of SN1987A the world's total sample of supernova neutrino events will - at last - be larger than it is today!

I'll see you then!